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Simons et al.

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(54) **MULTIMODE DIRECTIONAL COUPLER**

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(71) Applicant: **The United States of America, as represented by the Administrator of the National Aeronautics and Space Administration, Washington, DC (US)**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 21 days.

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Primary Examiner — William Hernandez

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H01P 5/12 (2006.01)
H01P 5/18 (2006.01)

(52) **U.S. Cl.**
CPC **H01P 5/18** (2013.01)

(58) **Field of Classification Search**
CPC H01P 5/12; H01P 5/16; H01P 5/18;
H01P 5/181
USPC 333/109–111, 113, 132, 134, 135
See application file for complete search history.

(57) **ABSTRACT**

A multimode directional coupler is provided. In some embodiments, the multimode directional coupler is configured to receive a primary signal and a secondary signal at a first port of a primary waveguide. The primary signal is configured to propagate through the primary waveguide and be outputted at a second port of the primary waveguide. The multimode directional coupler also includes a secondary waveguide configured to couple the secondary signal from the primary waveguide with no coupling of the primary signal into the secondary waveguide. The secondary signal is configured to propagate through the secondary waveguide and be outputted from a port of the secondary waveguide.

20 Claims, 13 Drawing Sheets

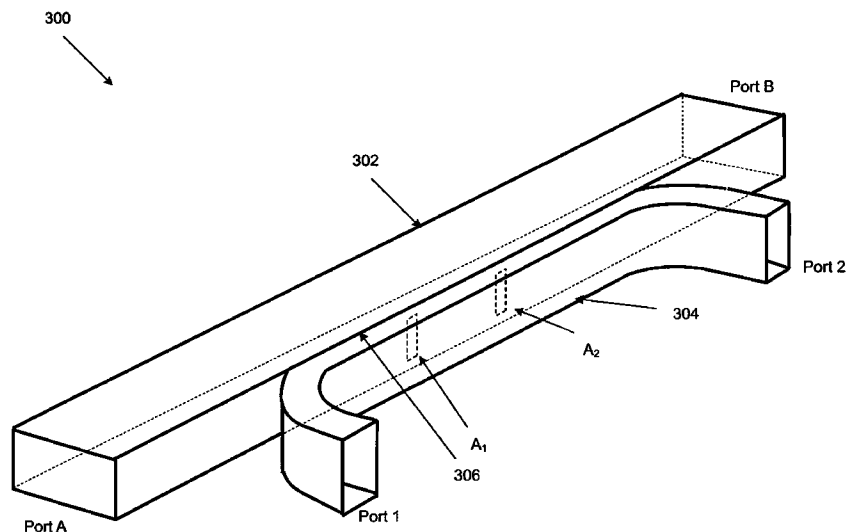


FIG. 1

Related Art

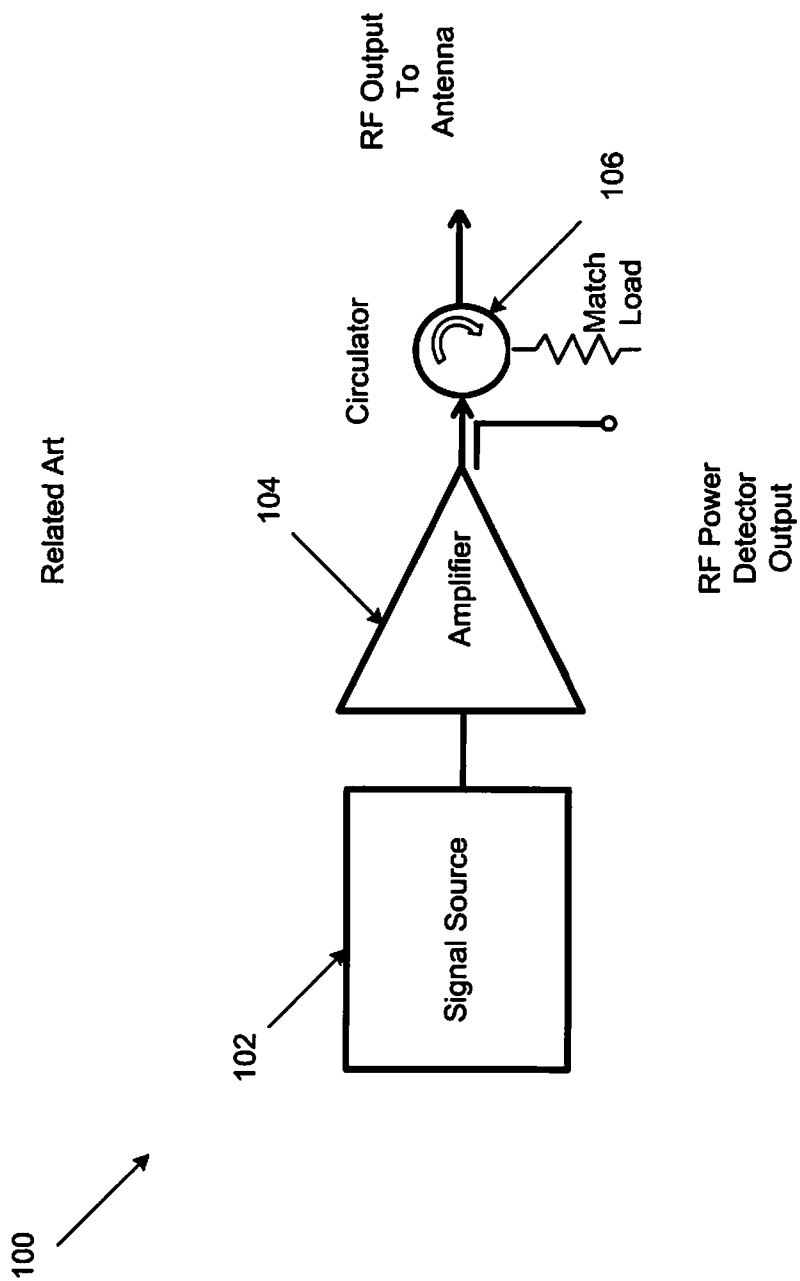


FIG. 2

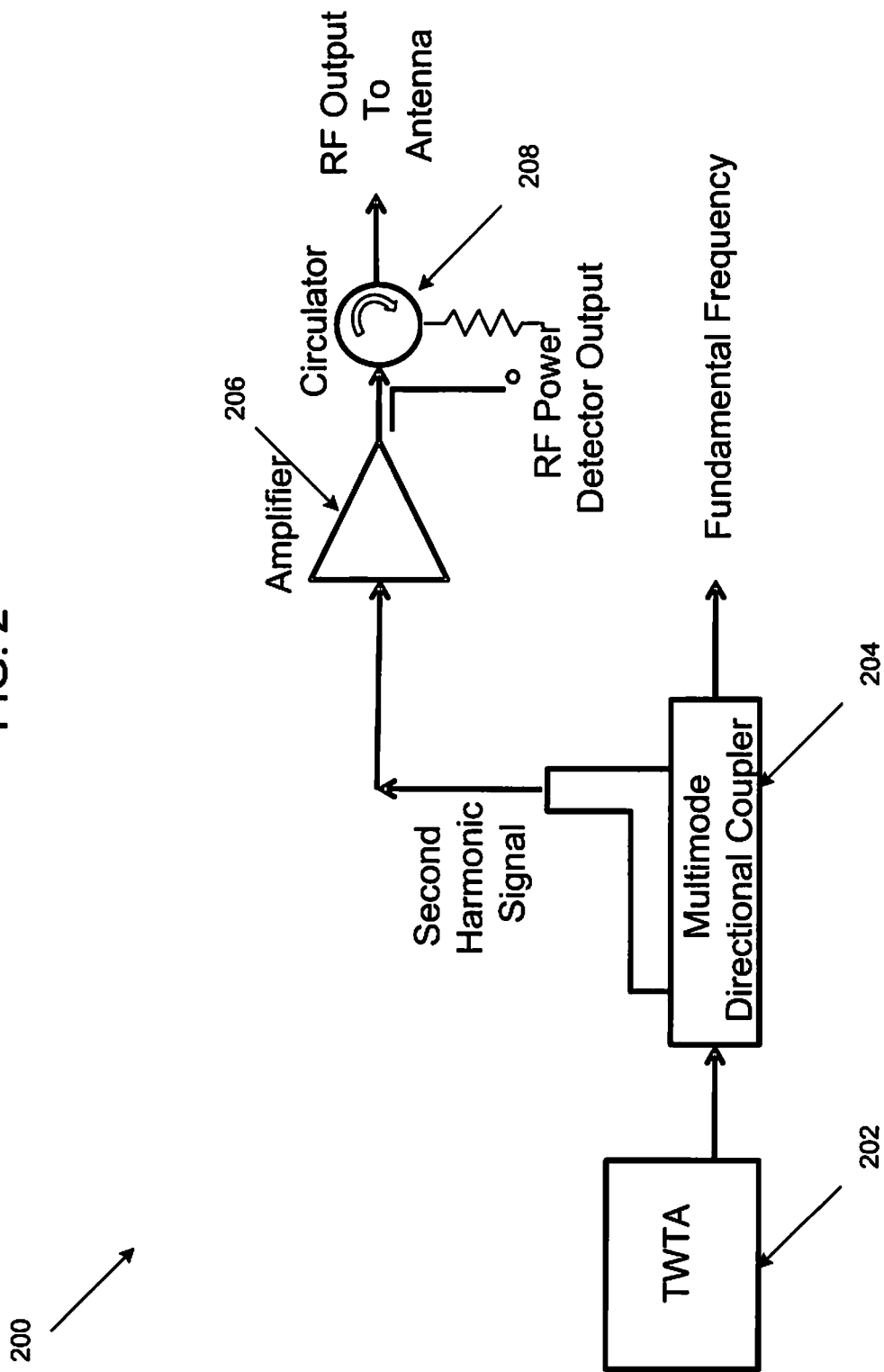


FIG. 3

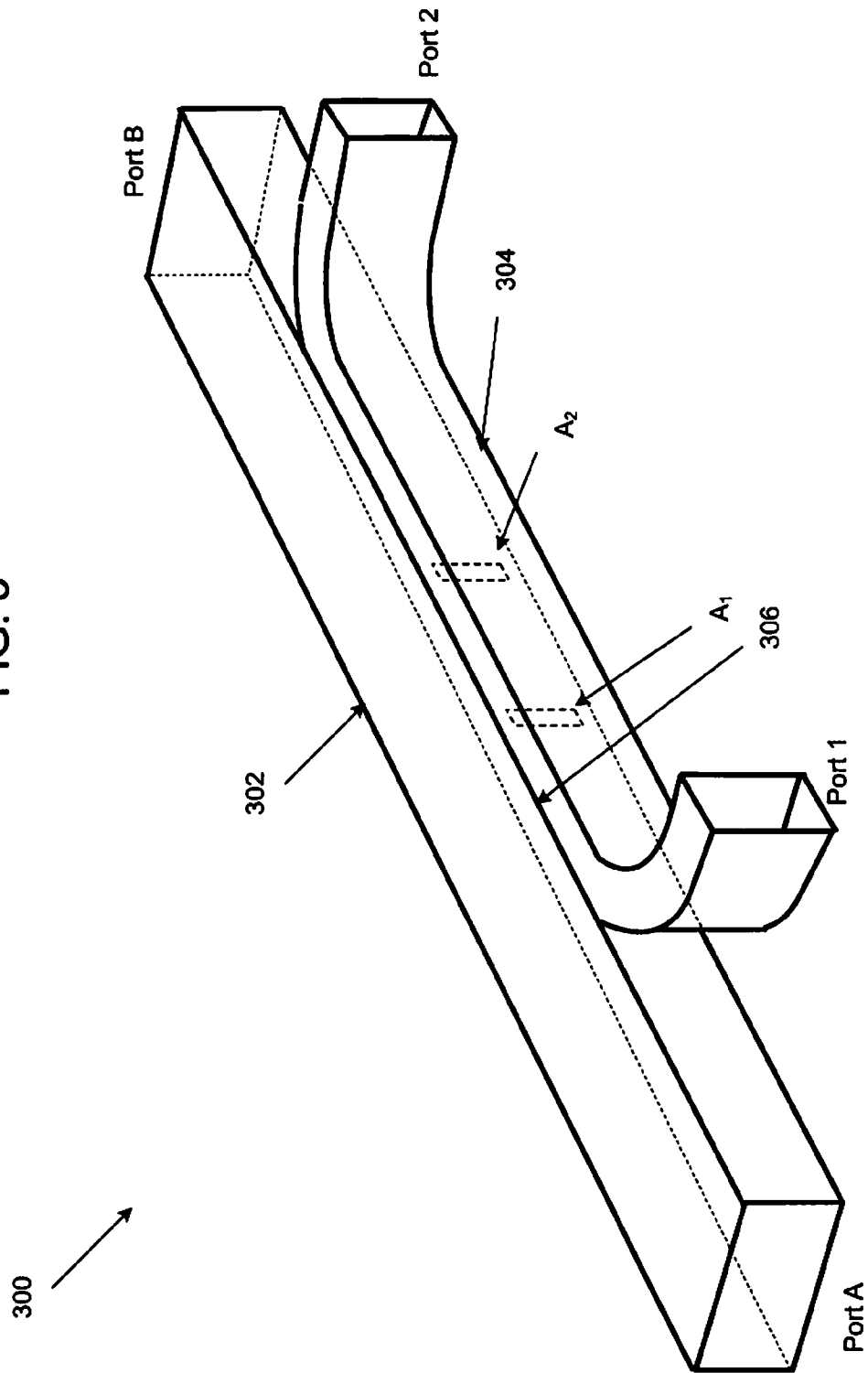


FIG. 4

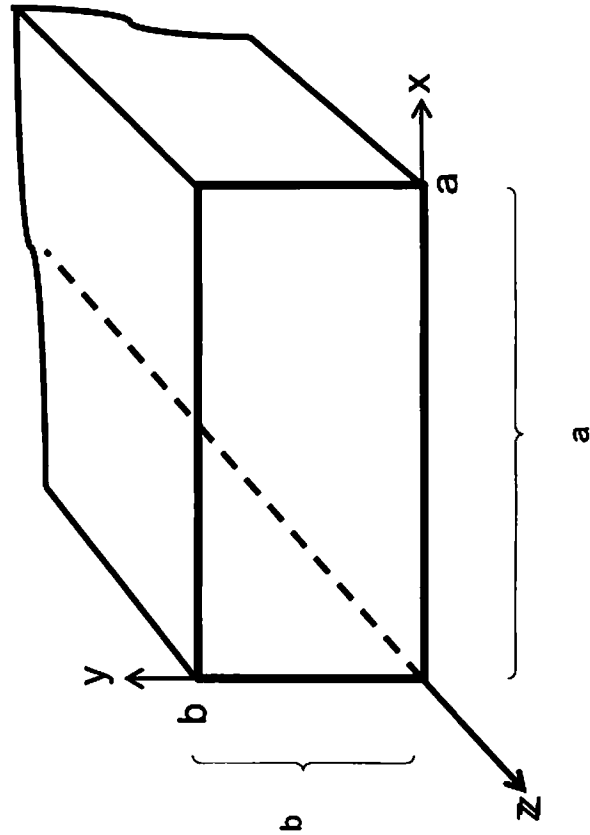


FIG. 5

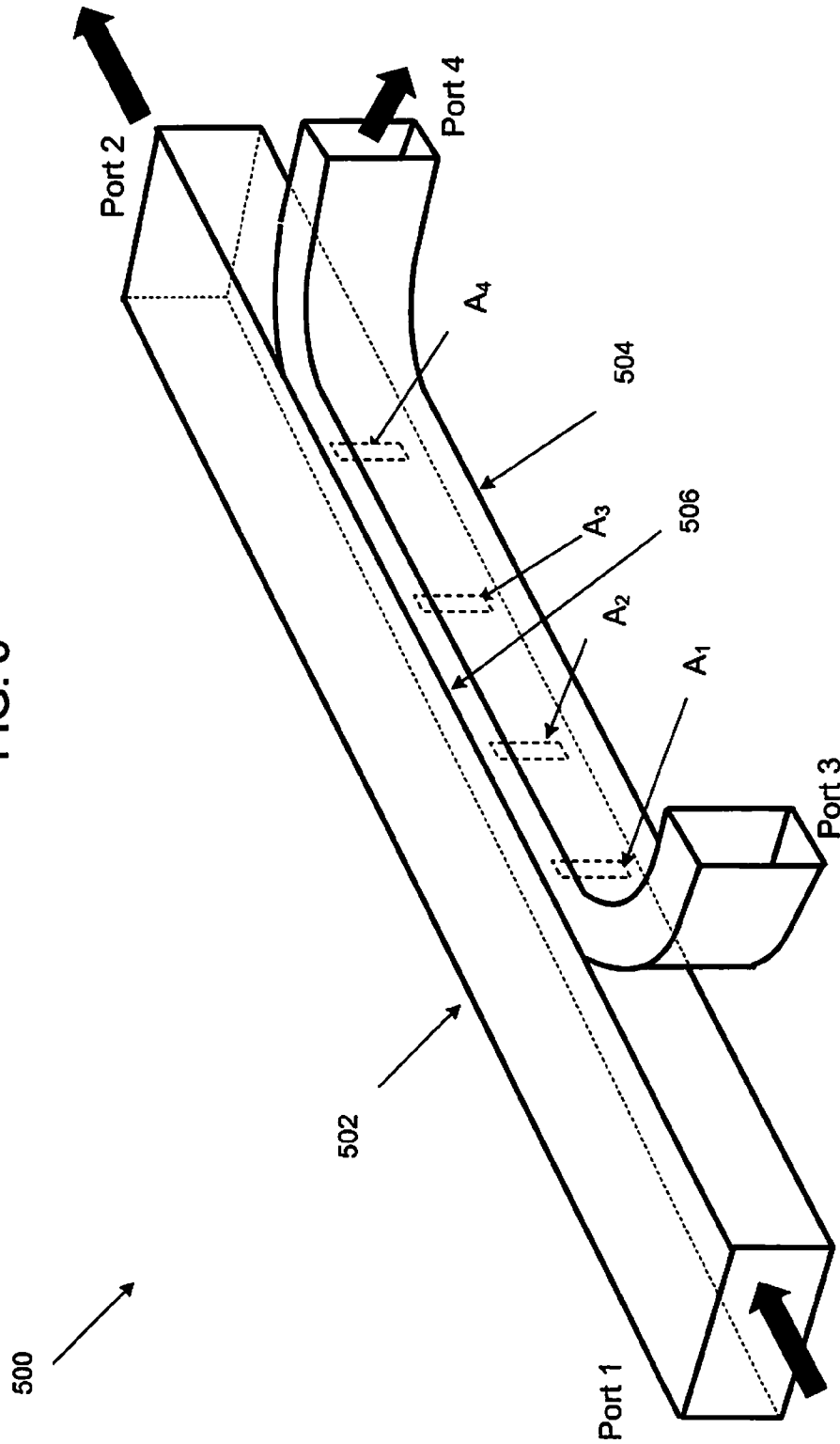


FIG. 6

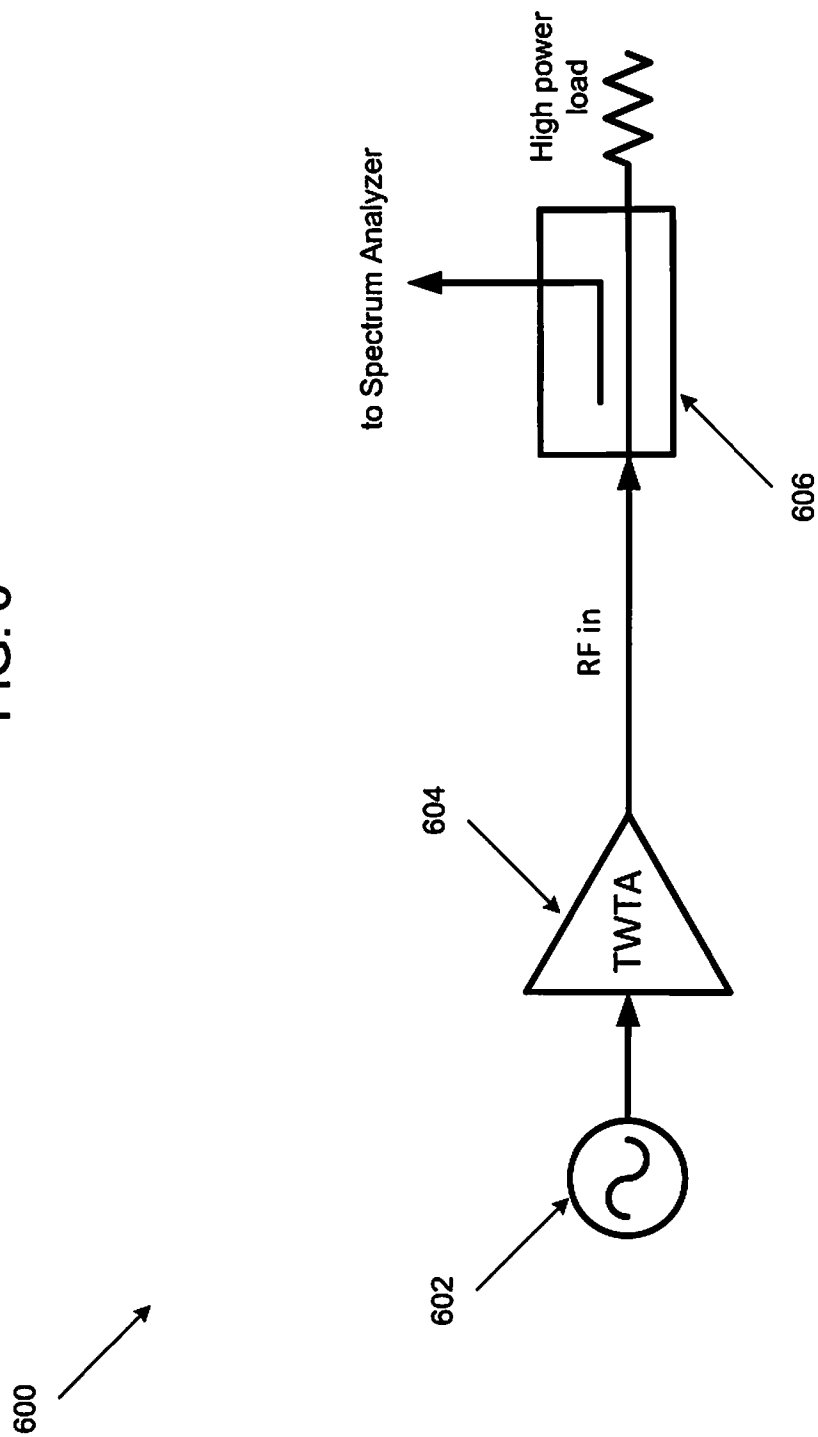
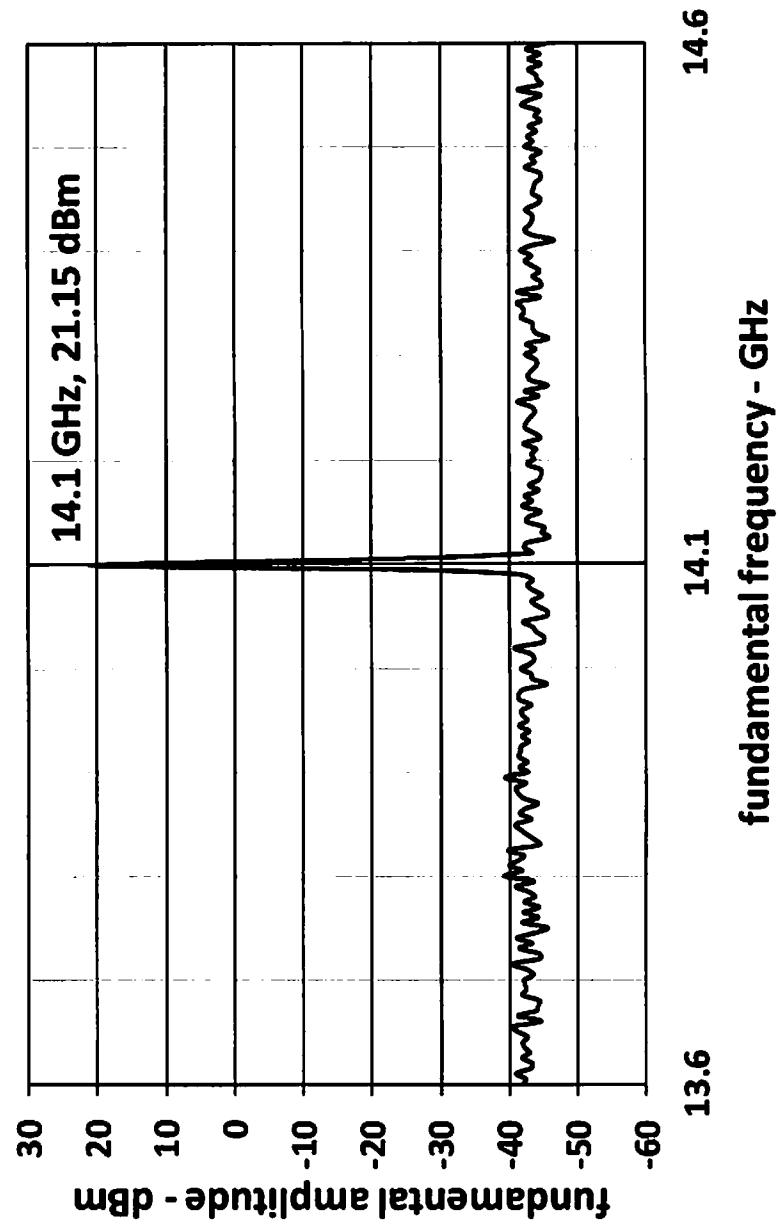


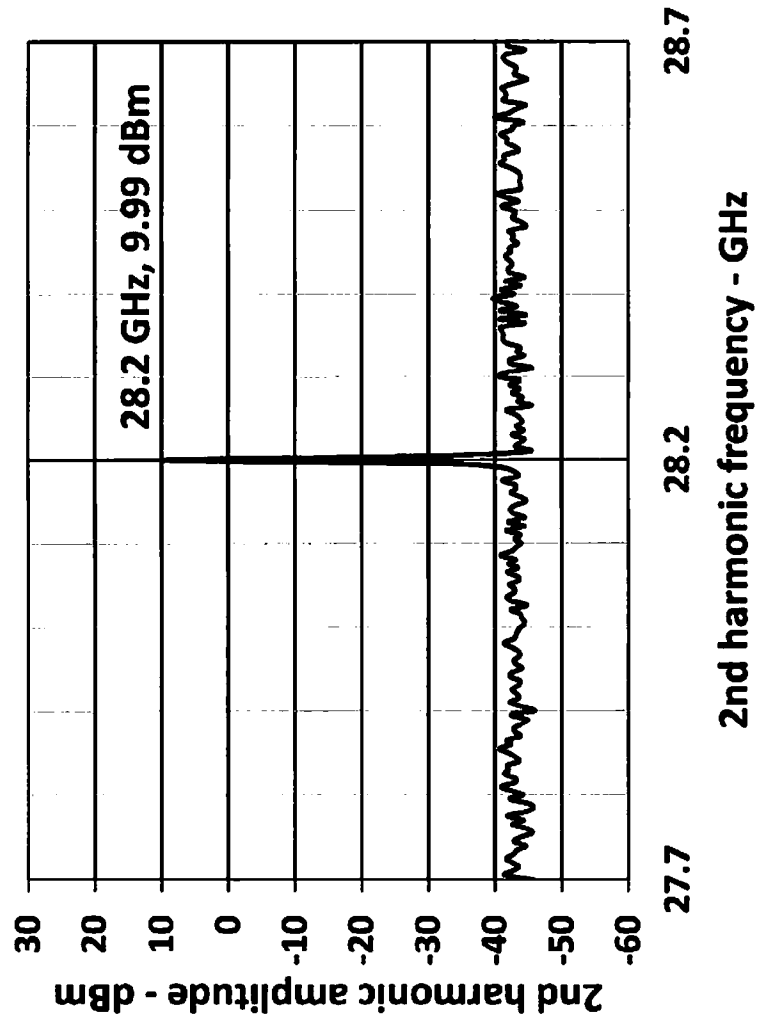
FIG. 7



700



FIG. 8



800

FIG. 9

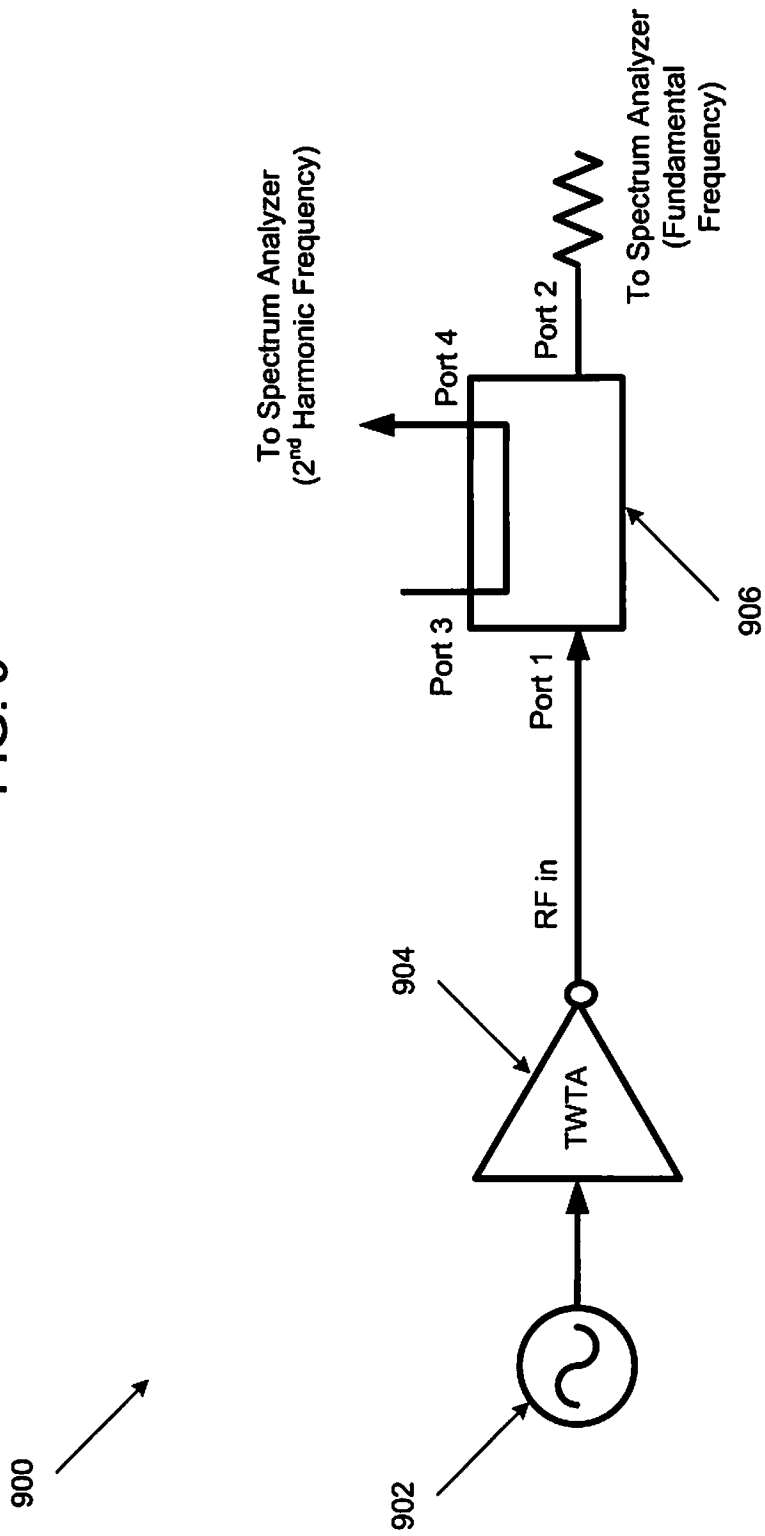
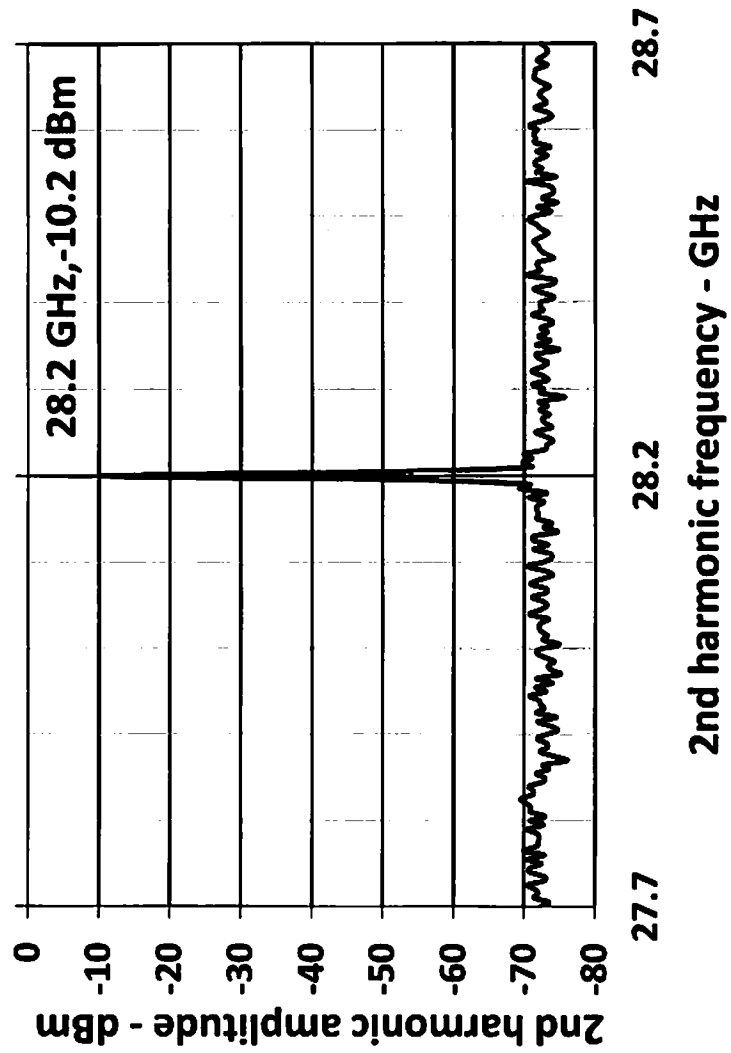


FIG. 10



1100



FIG. 11

1000

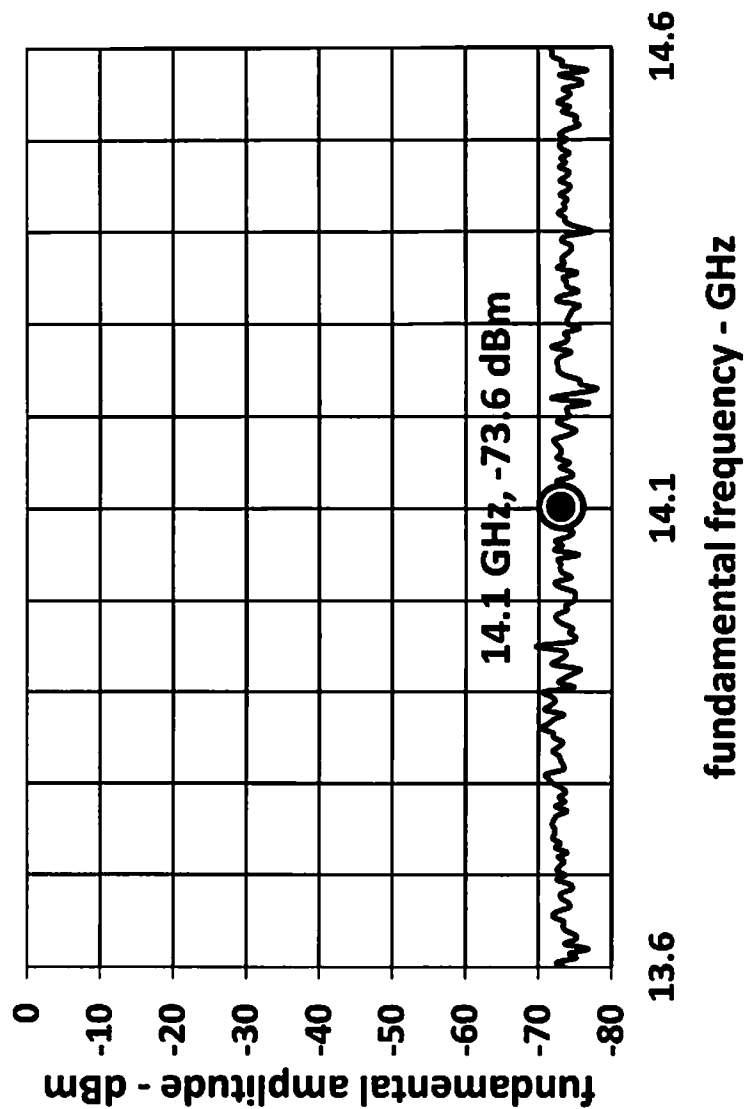

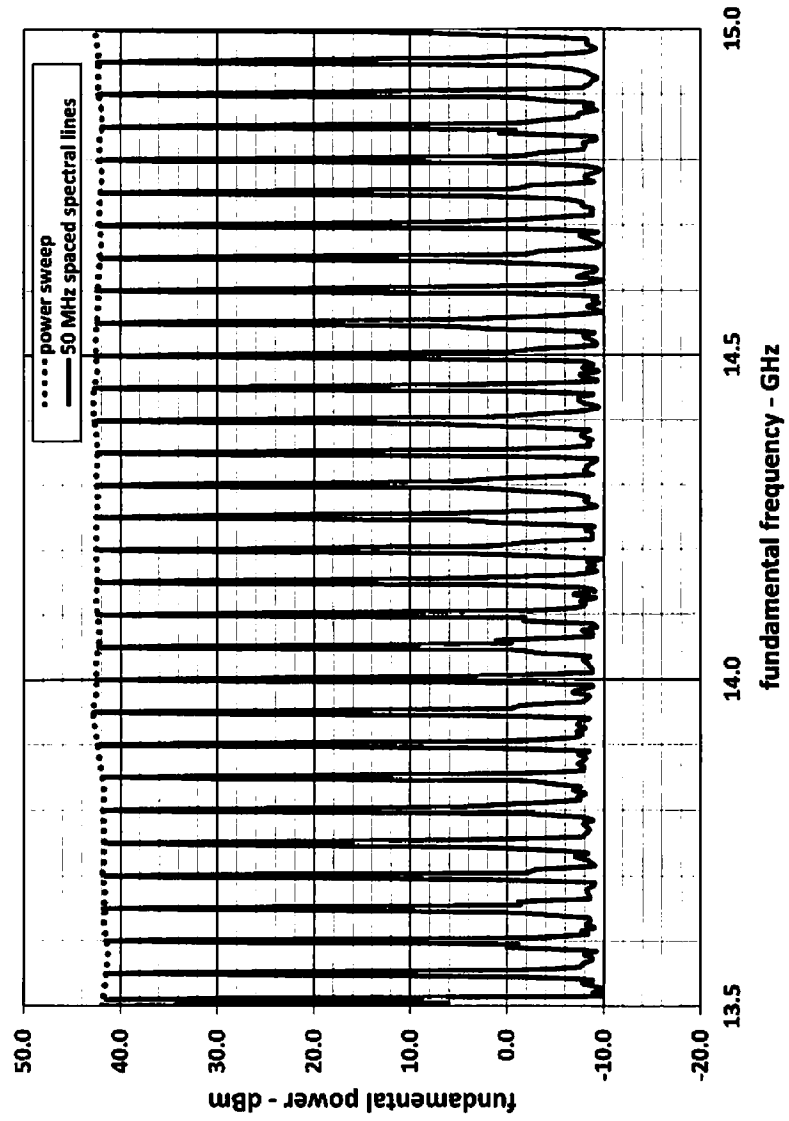


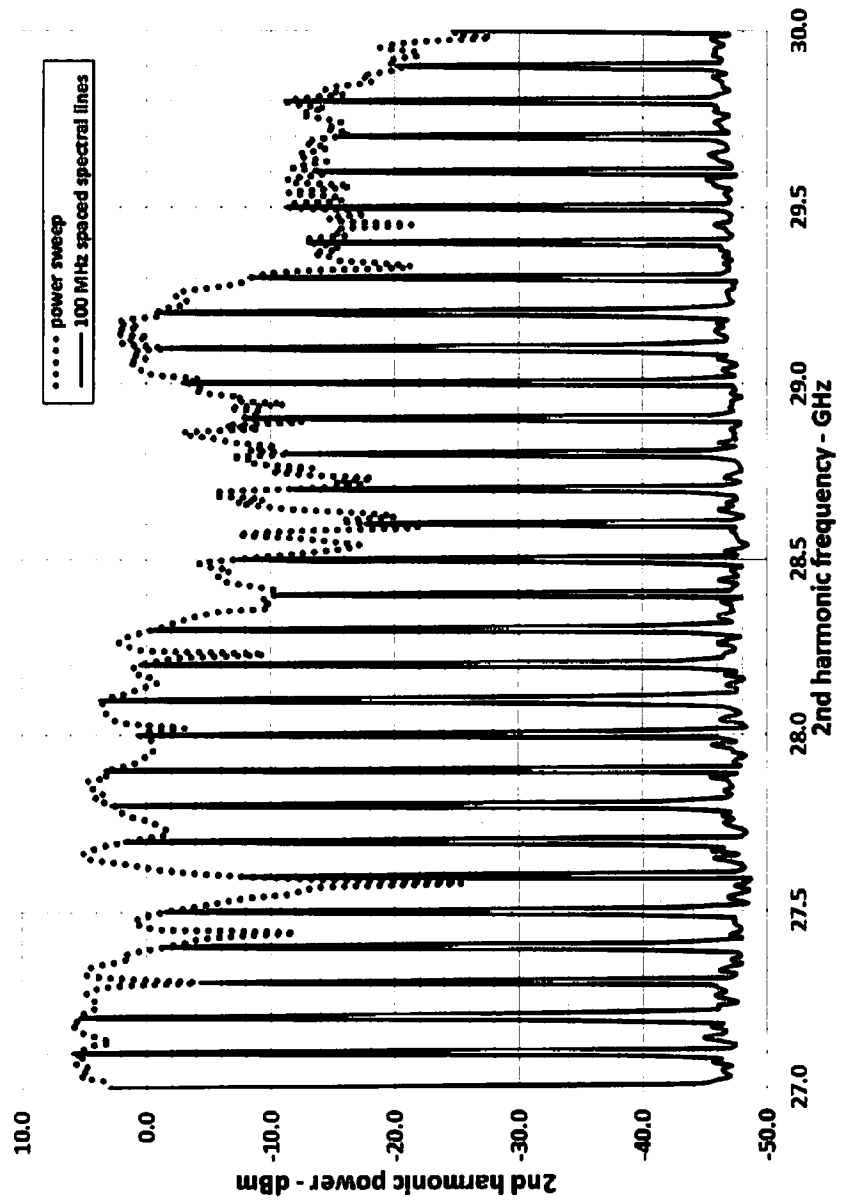
FIG. 12



1200



FIG. 13



1300



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MULTIMODE DIRECTIONAL COUPLER**CROSS-REFERENCE TO RELATED APPLICATION**

This application claims the benefit of U.S. Provisional Patent Application No. 61/724,359, filed on Nov. 9, 2012, the subject matter of which is hereby incorporated by reference in its entirety.

ORIGIN OF THE INVENTION

The invention described herein was made by employees of the United States Government and may be manufactured and used by or for the Government for Government purposes without the payment of any royalties thereon or therefore.

FIELD

The present invention relates to a multimode directional coupler and, more particularly, to a multimode directional coupler configured to extract 2^{nd} or higher harmonic signals from an amplifier.

BACKGROUND

When a higher frequency is desired for satellite communications, an atmosphere propagation study is generally required. For instance, a low power transmitter (e.g., a beacon source) is attached to the satellite. The low power transmitter normally does not transmit any data, but instead transmits a beacon (e.g., continuous waveform (CW) signal) to a receiving station on Earth. The receiving station studies include the CW signal fades, the signal propagation delay and the signal group velocity changes due to weather effects. This study is typically conducted over 3-5 years to obtain sufficient statistics. For instance, if the weather in a certain area has high rate of rain, then the statistics will show that the transmitter power may have to be increased. However, if the receiving station is located in a desert with little or no rain, the statistics may show that the transmitter power may not have to be increased.

However, with a conventional beacon source, as frequency is increased, it becomes a challenge to build a new beacon source for the transmitter on the satellite. This is because at higher frequencies, transistors do not function efficiently and tube manufacturing also becomes a challenge. Thus, a new beacon configuration or architecture may be beneficial.

SUMMARY

Certain embodiments of the present invention may provide solutions to the problems and needs in the art that have not yet been fully identified, appreciated, or solved by conventional beacon configurations. For instance, one or more embodiments of the present invention pertain to a multimode directional coupler configured to extract 2^{nd} or higher harmonic (e.g. 3^{rd} , 4^{th} , or 5^{th}) signals from a traveling wave tube amplifier (TWTA) with minimum perturbation to a fundamental signal. In some embodiments, a solid-state power amplifier (SSPA) or a microwave power module (MPM) may be utilized instead of the TWTA.

In one embodiment, an apparatus is provided. The apparatus includes a primary waveguide configured to propagate a fundamental signal from one port to another. The apparatus also includes a secondary waveguide configured to extract 2^{nd} or higher harmonic signals from the primary waveguide without perturbing the fundamental signal.

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In another embodiment, an apparatus is provided. The apparatus includes a primary waveguide configured to receive a primary signal and at least one secondary signal at a first port. The apparatus also includes a secondary waveguide configured to extract the at least one secondary signal from the primary waveguide such that the primary signal is prevented from coupling into the secondary waveguide.

In yet another embodiment, an apparatus is provided. The apparatus includes a primary waveguide configured to receive a dominant mode frequency and at least one higher order mode frequency. The apparatus also includes a secondary waveguide coupled to the primary waveguide that is configured to extract the at least one higher order mode frequency from the primary waveguide with minimum perturbation of the dominant mode frequency.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the advantages of certain embodiments of the invention will be readily understood, a more particular description of the invention briefly described above will be rendered by reference to specific embodiments that are illustrated in the appended drawings. While it should be understood that these drawings depict only typical embodiments of the invention and are not therefore to be considered to be limiting of its scope, the invention will be described and explained with additional specificity and detail through the use of the accompanying drawings, in which:

FIG. 1 is a schematic illustrating a conventional beacon configuration.

FIG. 2 is a schematic illustrating a beacon configuration using a 2^{nd} harmonic from a traveling wave tube amplifier (TWTA), according to an embodiment of the present invention.

FIG. 3 is a schematic illustrating a multimode directional coupler, according to an embodiment of the present invention.

FIG. 4 illustrates a cross-sectional segment of a rectangular guide, according to an embodiment of the present invention.

FIG. 5 is a schematic illustrating a multimode directional coupler, according to an embodiment of the present invention.

FIG. 6 is a schematic illustrating a test circuit for measurement of TWTA output power of fundamental and 2^{nd} harmonic frequencies, according to an embodiment of the present invention.

FIG. 7 is a graph illustrating a power level of a fundamental signal at TWTA saturation measured at TWTA output using a 13 dB broadband coaxial directional coupler, according to an embodiment of the present invention.

FIG. 8 is a graph illustrating a power level of a 2^{nd} harmonic signal at TWTA saturation measured at TWTA output using a 13 dB broadband coaxial directional coupler, according to an embodiment of the present invention.

FIG. 9 is a schematic illustrating a test circuit for measurement of fundamental and 2^{nd} harmonic frequencies at TWTA saturation, according to an embodiment of the present invention.

FIG. 10 is a graph illustrating a power level of a 2^{nd} harmonic measured at the output of Port 4 of a multimode directional coupler, according to an embodiment of the present invention.

FIG. 11 is a graph illustrating a power level of a fundamental signal measured at the output of Port 4 of a multimode directional coupler, according to an embodiment of the present invention.

FIG. 12 is a graph illustrating the measured radio frequency power at Port 2 of the multimode directional coupler

at Ku-band fundamental frequencies, according to an embodiment of the present invention.

FIG. 13 is a graph illustrating the measured radio frequency power at Port 4 of the multimode directional coupler at Ka-band 2nd harmonic frequencies, according to an embodiment of the present invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

FIG. 1 is a schematic 100 illustrating a conventional beacon configuration. The conventional beacon configuration may include a Q-band or V-band signal source 102 configured to generate a signal. Because the frequency spectrum is divided into bands, signals operating in 26.5 to 40 Gigahertz (GHz) are known as Ka-band signals, signals operating in 33-50 GHz are known as Q-band signals, signals operating in 50-75 GHz are known as V-band signals, and signals operating in the 75-110 GHz are known as W-band signals. An amplifier 104 amplifies or excites the signal, and a circulator 106 transmits the amplified signal (e.g., radio frequency (RF) output) to an antenna, such that the amplified signal can be transmitted to a receiving station on Earth. Circulator 106 also couples any reflections from the antenna to a match load. Also, a RF power detector monitors the amount of power that the beacon outputs from amplifier 104.

With the conventional beacon configuration, as frequency is increased, it becomes a challenge to develop a new beacon source for the transmitter on the satellite. Because at higher frequencies, transistors do not function efficiently and tube manufacturing also becomes a challenge. Instead of building a new beacon source each time a higher frequency is desired, a beacon configuration using 2nd or higher harmonic from a traveling wave tube amplifier (TWTA) 202 may be beneficial. For instance, a multimode coupler in some embodiments may be used to couple the 2nd or higher harmonic power, which can be amplified, and transmit it down to a receiving station on Earth.

FIG. 2 is a schematic 200 illustrating a beacon configuration using a 2nd harmonic from a TWTA, according to an embodiment of the present invention. In this embodiment, TWTA 202 receives a signal from a signal source (not shown). In other embodiments, a solid-state power amplifier (SSPA) or a microwave power module (MPM) may be utilized instead of the TWTA. The signal source may be a Ku-band signal source, a Ka-band signal source, or a signal source in any band that would be appreciated by a person of ordinary skill in the art.

TWTA 202 may amplify the received signal and transmit the amplified signal to a multimode directional coupler 204. Multimode directional coupler 204 may select (or separate) the 2nd or higher harmonic power signal from the fundamental frequency (or signal), and transmit the 2nd or higher harmonic power signal to amplifier 206 to be amplified. The amplified 2nd harmonic power signal may pass through a circulator 208 to an antenna to be transmitted to a receiving station on Earth.

In one example, if the signal source outputs a Ku-band signal at 14 GHz, the 2nd harmonic power of the Ku-band signal is at 28 GHz. Multimode direction coupler 204 in this example would select the 2nd harmonic power signal of the Ku-band signal, such that 2nd harmonic power signal of the Ku-band signal is amplified and circulated prior to transmission to the receiving station. It should also be appreciated that depending on the design of multimode directional coupler

204, the 2nd or higher harmonic power signal of a Ka-band signal, a Q-band signal, a V-band signal, or a W-band signal may be separated.

It should be appreciated that the fundamental frequency signal carrying the science data from an assortment of instruments onboard the satellite or spacecraft may be transmitted to its appropriate destination by separate antennas.

FIG. 3 is a schematic 300 illustrating a multimode directional coupler, according to an embodiment of the present invention. In this embodiment, a primary waveguide 302 having Ports A and B is connected to a secondary waveguide 304 having Ports 1 and 2. The fundamental frequency (or signal), which is the output of TWTA 202 shown in FIG. 2, travels through primary waveguide 302, and the 2nd or higher harmonic frequency (or signal), which may be separated from the fundamental signal, and travels through secondary waveguide 304. Some embodiments may include more than one higher order mode frequency.

It should be appreciated that the dimensions of primary waveguide 302 and secondary waveguide 304 are different. For example, if a Ka-band signal is operating at 30-35 GHz, the 2nd harmonic power of the Ka-band signal may operate at 60-70 GHz. This may cause the 2nd harmonic power to operate in V-band. To accommodate these frequencies, the dimensions of secondary waveguide 304 are different from those of primary waveguide 302. In other words, the dimensions of primary waveguide 302 and secondary waveguide 304 vary according to the frequency of the fundamental and the 2nd or higher harmonic signals.

It should be noted that in this embodiment primary waveguide 302 and secondary waveguide 304 share a common wall 306. Wall 306 may include apertures A₁, A₂. Apertures A₁, A₂ may have a rectangular opening, a rectangular opening with rounded corners, a circular opening, or any type of arbitrary shaped opening that would be appreciated by a person of ordinary skill in the art. Depending on the desired band, the height, width and shape of each aperture A₁, A₂ and the distance between each aperture A₁, A₂ may vary. Furthermore, the number of apertures may also vary depending on the desired coupling and bandwidth. See, for example, FIG. 5, which shows more than two apertures.

Generally, when a waveguide is designed, the waveguide is configured to carry the signal power in the fundamental mode only. For example, primary waveguide 302 may propagate the fundamental signal, e.g., dominant transverse electric (TE₁₀) mode, from Port A to Port B. However, when a 2nd or higher harmonic signal is in primary waveguide 302, the 2nd or higher harmonic signal will propagate as a higher order (transverse magnetic (TM_{mn}) and transverse electric TE_{mn}) modes. For example, in order to sample the 2nd harmonic signal, apertures A₁, A₂ are configured to couple to the higher order modes, i.e., the TM₁₁ and TE₁₁ modes. This allows the 2nd harmonic signal to propagate through secondary waveguide 304. In other words, apertures A₁, A₂ are configured to prevent the fundamental signal in primary waveguide 302 from coupling into secondary waveguide 304, while allowing the 2nd harmonic signal to enter into, and propagate through, secondary waveguide 304.

FIG. 4 is a cross-sectional segment 400 illustrating a rectangular waveguide, according to an embodiment of the present invention. In particular, FIG. 4 shows a coordinate system of a rectangular waveguide. In this embodiment, for a primary waveguide, as shown in FIG. 3, the x-axis is the horizontal axis and the y-axis is the vertical axis. The waveguide may have a width 'a' and a height 'b'. The z-direction is the direction in which the signal propagates.

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However, for a secondary waveguide, as shown in FIG. 3, the x-axis is now the vertical axis, and the y-axis is now the horizontal axis. The z-direction remains the direction in which the 2nd harmonic signal propagates. Stated differently, the secondary waveguide may be rotated 90 degrees to the primary waveguide. This allows the 2nd harmonic signal to propagate through the apertures into the secondary waveguide. It should be appreciated that in some embodiments the cross-section of the secondary waveguide is smaller than that of the primary waveguide. For example, the primary waveguide could be WR-62 for a fundamental signal at Ku-band and the secondary waveguide could be WR-28 for a 2nd harmonic signal at Ka-band.

FIG. 5 is a schematic 500 illustrating a multimode directional coupler, according to an embodiment of the present invention. In this embodiment, a primary waveguide 502 is operably connected to a secondary waveguide 504 using a common wall 506. Wall 506 includes four apertures A₁, A₂, A₃, and A₄.

In this embodiment, the fundamental signal, including the 2nd harmonic signal, enters primary waveguide 502 through Port 1. The fundamental signal propagates through primary waveguide 502, and exits from Port 2 of primary waveguide 502 with minimum perturbation. Apertures A₁, A₂, A₃, A₄ are configured to separate the 2nd harmonic signal from the fundamental signal. For example, each aperture A₁, A₂, A₃, A₄ is configured to allow the 2nd harmonic signal to couple into secondary waveguide 504. As portions of the 2nd harmonic signal couple into secondary waveguide 504 through the apertures, each of the coupled portions of the 2nd harmonic signal reinforce each other to form the output 2nd harmonic signal. It should be appreciated that the 2nd harmonic signal becomes the dominant frequency in secondary waveguide 504. The reinforced 2nd harmonic signal may then propagate through secondary waveguide 504 and exit from Port 4, such that the 2nd harmonic signal can be used as a beacon source. This beacon source signal may then be transmitted to a receiving station for radio wave propagation study through the Earth's atmosphere.

It should be noted that when the 2nd harmonic signal is coupled out of primary waveguide 502, 100 percent of the 2nd harmonic signal is not realized in secondary waveguide 504. In order to increase the coupling efficiency, a greater number of apertures may be used. By using more apertures, a greater number of coupling of portions of the 2nd harmonic signal occur. This allows for a stronger (i.e., more reinforced) 2nd harmonic signal to be produced, requiring a lesser amount of amplification of the 2nd harmonic signal. However, it should be noted that the optimum number of apertures depends on the size of the multimode directional coupler. Further, as discussed above, the height and width of, and the distance between, each aperture may vary depending on the desired bandwidth and coupling.

FIG. 6 is a schematic 600 illustrating a test circuit for measurement of TWTA output power of fundamental and 2nd harmonic frequencies, according to an embodiment of the present invention. The test circuit of FIG. 6 is used to measure the output power levels of the fundamental signal and 2nd harmonic signal from TWTA 604. In this embodiment, signal source 602 generates a fundamental frequency signal (or frequency signal) and a TWTA 604 amplifies the frequency signal.

The amplified frequency signal travels to a broadband coaxial directional coupler 606. A small sample of the amplified frequency signal is coupled by the broadband coaxial directional coupler 606, and is transferred to a spectrum analyzer (not shown) so the power levels of the fundamental

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signal and the 2nd harmonic signals can be analyzed. Broadband coaxial directional coupler 606, in certain embodiments, couples a portion of both the fundamental and the 2nd harmonic signals.

In this example, the spectrum analyzer can measure and compare the TWTA output power at the fundamental and 2nd harmonic signal frequencies. See, for example, FIGS. 7 and 8.

In FIG. 7, graph 700 shows that the power level for the fundamental signal at 14.1 GHz as 21.15 dBm. In FIG. 8, graph 800 shows that the power level for the 2nd harmonic signal at 28.2 GHz as 9.99 dBm. FIG. 8 further indicates that the signal strength at 28.2 GHz is strong, as it is 9.99 dBm. In other words, graphs of FIGS. 7 and 8 show the presence of both the fundamental signal as well as a strong 2nd harmonic signal at TWTA radio frequency output.

FIG. 9 is a schematic 900 illustrating a test circuit for measurement of fundamental and 2nd harmonic frequencies at TWTA saturation, according to an embodiment of the present invention. In particular, the test circuit of FIG. 9 is used to establish that multimode directional coupler 500 of FIG. 5 efficiently couples the 2nd harmonic signal to secondary waveguide 504 and also prevents the fundamental signal from coupling into secondary waveguide 504.

In this embodiment, a signal source 902 generates a 14.1 GHz fundamental frequency, and a TWTA 904 amplifies the fundamental frequency. The amplified fundamental frequency may then enter multimode directional coupler 906. Multimode directional coupler 906 may be similar to multimode directional coupler 500 of FIG. 5. A spectrum analyzer (not shown) is connected to Port 2 and Port 4 of multimode directional coupler 906. This allows the spectrum analyzer to measure and compare the power levels of the fundamental signal from Port 2 with the 2nd harmonic signal output from Port 4. In addition, this configuration also allows validating that the fundamental signal does not couple to the secondary waveguide. See, for example, FIGS. 10 and 11.

FIG. 10 is a graph 1000 illustrating a power level of a 2nd harmonic measured at the output of Port 4 of a multimode directional coupler, according to an embodiment of the present invention. FIG. 11 is a graph 1100 illustrating a power level of a fundamental signal measured at the output of Port 4 of a multimode directional coupler, according to an embodiment of the present invention. In particular, graph 1100 of FIG. 11 shows that the fundamental signal does not couple into the secondary waveguide of the multimode directional coupler, as the signal strength of the fundamental signal measured at Port 4 is at -73.6 dBm or smaller.

Using the test circuit shown in FIG. 9, FIG. 12 shows a graph 1200 illustrating the measured radio frequency power at Port 2 of the multimode directional coupler at several Ku-band fundamental frequencies in the 13.5 to 15.0 GHz range. FIG. 13 also shows a graph 1300 illustrating the measured radio frequency power at Port 4 of the multimode directional coupler at the corresponding Ka-band 2nd harmonic frequencies in the 27 to 30 GHz range. The measured data shows the presence of a strong 2nd harmonic signal over a wide range of frequencies, which could be used as a beacon source for radio wave propagation studies.

Some embodiments of the present invention pertain to a multimode directional coupler configured to receive a primary signal and a secondary signal at a first port of a primary waveguide. The primary signal is configured to propagate through the primary waveguide and output at a second port of the primary waveguide. The multimode directional coupler also includes a secondary waveguide configured to couple the secondary signal from the primary waveguide with no coupling of the primary signal into the secondary waveguide. The

secondary signal is configured to propagate through the secondary waveguide and output from a port of the secondary waveguide.

It will be readily understood that the components of the invention, as generally described and illustrated in the figures herein, may be arranged and designed in a wide variety of different configurations. Thus, the detailed description of the embodiments is not intended to limit the scope of the invention as claimed, but is merely representative of selected embodiments of the invention.

The features, structures, or characteristics of the invention described throughout this specification may be combined in any suitable manner in one or more embodiments. For example, the usage of “certain embodiments,” “some embodiments,” or other similar language, throughout this specification refers to the fact that a particular feature, structure, or characteristic described in connection with an embodiment may be included in at least one embodiment of the invention. Thus, appearances of the phrases “in certain embodiments,” “in some embodiments,” “in other embodiments,” or other similar language, throughout this specification do not necessarily all refer to the same embodiment or group of embodiments, and the described features, structures, or characteristics may be combined in any suitable manner in one or more embodiments.

One having ordinary skill in the art will readily understand that the invention as discussed above may be practiced with steps in a different order, and/or with hardware elements in configurations that are different than those which are disclosed. Therefore, although the invention has been described based upon these preferred embodiments, it would be apparent to those of skill in the art that certain modifications, variations, and alternative constructions would be apparent, while remaining within the spirit and scope of the invention. In order to determine the metes and bounds of the invention, therefore, reference should be made to the appended claims.

What is claimed is:

1. An apparatus, comprising:

a primary waveguide having a first longitudinal axis and configured to propagate a fundamental signal from one port of the primary waveguide to another port of the primary waveguide; and

a secondary waveguide having a second longitudinal axis parallel to the first longitudinal axis wherein the second waveguide is rotated 90 degrees about the second longitudinal axis and configured to extract a second or higher harmonic signal from the primary waveguide with minimum perturbation to the fundamental signal.

2. The apparatus of claim 1, wherein the secondary waveguide is further configured to propagate the second or higher harmonic signal and output the second or higher harmonic signal from a port of the secondary waveguide.

3. The apparatus of claim 1, wherein the primary waveguide and the secondary waveguide share a common wall.

4. The apparatus of claim 3, wherein the common wall comprises a plurality of apertures, each of the plurality of apertures comprising a rectangular aperture, a rectangular aperture with rounded edges, a circular aperture, or an arbitrary shaped aperture.

5. The apparatus of claim 4, wherein each of the plurality of apertures is configured to couple a portion of the second or higher harmonic signal from the primary waveguide into the secondary waveguide such that the second or higher harmonic signal is formed in the secondary waveguide.

6. The apparatus of claim 4, wherein each of the plurality of apertures has a longitudinal axis which is perpendicular or

substantially perpendicular to the first longitudinal axis of the primary waveguide and is configured to prevent the fundamental signal from coupling into the secondary waveguide.

7. The apparatus of claim 1, wherein the primary waveguide is configured to receive the fundamental signal and the second or higher harmonic signal at a first port.

8. An apparatus, comprising:

a primary waveguide having a first longitudinal axis and configured to propagate a fundamental signal and receive a primary signal and a secondary signal at a first port; and

a secondary waveguide having a second longitudinal axis parallel to the first longitudinal axis wherein the second waveguide is rotated 90 degrees about the second longitudinal axis and configured to extract the secondary signal from the primary waveguide such that the primary signal is prevented from coupling into the secondary waveguide.

9. The apparatus of claim 8, wherein the primary signal is configured to propagate through the primary waveguide and be outputted from a second port of the primary waveguide.

10. The apparatus of claim 9, wherein the secondary signal is configured to propagate through the secondary waveguide and be outputted from a port of the secondary waveguide.

11. The apparatus of claim 9, wherein the primary signal comprises a dominant mode frequency of a signal source.

12. The apparatus of claim 9, wherein the secondary signal comprises at least one higher order mode frequency of a signal source.

13. The apparatus of claim 9, further comprising:

a common wall configured to connect the primary waveguide and the secondary waveguide.

14. The apparatus of claim 13, wherein the common wall comprises a plurality of apertures.

15. The apparatus of claim 14, wherein each of the plurality of apertures has a longitudinal axis which is perpendicular or substantially perpendicular to the first longitudinal axis of the primary waveguide and is configured to extract a portion of the secondary signal from the primary waveguide into the secondary waveguide to form the secondary signal.

16. The apparatus of claim 14, wherein each of the plurality of apertures is configured to prevent the fundamental signal from coupling into the secondary waveguide.

17. An apparatus, comprising:

a primary waveguide having a first longitudinal axis and configured to receive a dominant mode frequency and at least one higher order mode frequency; and

a secondary waveguide having a second longitudinal axis parallel to the first longitudinal axis wherein the second waveguide is rotated 90 degrees about the second longitudinal axis and coupled to the primary waveguide, and configured to extract the at least one higher order mode frequency from the primary waveguide with minimum perturbation of the dominant mode frequency.

18. The apparatus of claim 17, further comprising:

a common wall comprising a plurality of apertures, and configured to couple the primary waveguide with the secondary waveguide.

19. The apparatus of claim 18, wherein each of the plurality of apertures has a longitudinal axis which is perpendicular or substantially perpendicular to the first longitudinal axis of the primary waveguide and is configured to extract a portion of the at least one higher order mode frequency from the primary waveguide to form the at least one higher order mode frequency in the secondary waveguide, the at least one higher order mode frequency is a dominant mode frequency of the secondary waveguide.

20. The apparatus of claim 17, wherein the at least one higher order mode frequency comprises a second or higher harmonic signal of a signal source.

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